

Profitability Optimization of Photovoltaic Storage Systems Using Simulation of Hourly Production and Load Profiles and a Total Cash Flow Model

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DOI

10.25673/OJS-auasr-3237-1777531308

ARTICLE HISTORY

2025, Dec 15 received
2026, Feb 10 received in revised form
2026, Feb 11 accepted
2026, May 11 published

KEYWORDS

Photovoltaic system, Battery Energy Storage System, Self-consumption energy system, Investment Analysis, Total Cash Flow Model (TCM), Profitability KPIs

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ABSTRACT

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Photovoltaic (PV) systems are increasingly popular in Germany due to high electricity prices and decreasing costs of PV components. Self-generation of electricity becomes attractive, but excess energy production fed into the grid is less valuable due to low feed-in tariff. Adding battery storage can increase self-consumption, reducing both grid dependency and minimizing excess production. However, profitability depends on the cost-benefit ratio of batteries, influenced by the hourly electricity consumption profile and seasonal efficiency of production.

A new method using a simulation framework is introduced to assess the profitability of PV systems and optimal battery sizes. This combines hourly weather data from a typical meteorological year (TMY) with hourly electricity consumption profiles to simulate generation, storage, and grid dependency. The resulting data informs financial cash flow plans and delivers profitability indicators based on system design and size.

This approach improves traditional methods by employing high-resolution hourly data for precise battery and PV sizing to maximize returns. Instead of the usual Net Present Value (NPV), the method uses Final Asset Value (FAV) for its insights into parameter development over an investment's lifespan.

A case study of a farming enterprise in Saxony-Anhalt, which already operates a profitable PV system, demonstrates the new method's application. An investment in additional battery storage is considered, and the battery capacity (kWh) is optimized.

1. Introduction

The integration of energy storage into residential photovoltaic (PV) systems is driven by two main considerations. First, residential and commercial PV owners seek to reduce their reliance on grid-supplied electricity. Second, utility operators aim to mitigate the operational challenges associated with the variable and non-dispatchable nature of PV generation. Therefore, a fundamental challenge in using solar energy is the timing mismatch between production and demand. When local PV generation exceeds consumption, the utility grid must absorb the surplus; conversely, when demand exceeds generation, like during nighttime or periods of low sunlight irradiance, the grid must supply the deficit.

The fraction of PV energy that is consumed at the moment it is generated is referred to as instantaneous energy self-consumption (IESC). IESC requires temporal coincidence between PV generation and load demand and is therefore inherently limited by the unpredictable behavior of both weather conditions and consumption patterns. Because these patterns are highly variable and hard to predict accurately, the achievable IESC in a system without storage is limited. Adding an energy buffer in the form of storage increases the system's ability to meet demand using both current PV production and previously stored energy. Choosing the right storage capacity is therefore a key design decision. Since battery systems involve significant capital and replacement costs, as well as limited service-lifetimes, the optimal capacity must be determined to ensure the long-term economic success of the system.

The optimal storage size directly depends on 4 key parameters:

1. The amount of surplus PV generation that is not consumed instantaneously. Accurately estimating this surplus requires high-resolution information on both weather conditions and load profiles.
2. The energy price in ct/kWh for energy consumed from the grid. The higher the energy price, the greater the profit impact of investing in battery storage capacity.
3. The specific price in EUR/kWh for investment in a battery storage system: The higher the battery costs, the lower the profitability of investing in battery storage capacity.
4. The financial discount rate which represents the profitability of alternative investments in the capital market instead of investing in battery storage capacity.

Therefore, any sizing method aimed at maximizing profitability should rely on both, hourly data sets of meteorological conditions at the installation site and the electricity consumption profile of the user. Hourly or even sub-hourly resolution is essential for characterizing the alignment between PV production and demand over time.

2. Materials and Methods: PV Plant Simulation Using Hourly Production and Load Profiles as a Basis for Financial Optimization

To determine the optimal storage size of a PV plant, the battery investment is compared to a cash investment in the capital market over a similar lifespan. A battery is considered the better investment if the cash surplus after 10 years (the lifespan of the battery)

exceeds that of a capital market investment. The optimal battery size yields the highest cash surplus.

To calculate the cash surplus of the investment, the energy yield from the battery investment is simulated using hourly production and load profiles of the PV plant. Energy production is based on hourly weather data of a typical meteorological year (TMY), while energy consumption relies on a representative annual load profile that reflects typical hourly consumption patterns at the site.

The optimal battery size is the one that provides the highest Final Asset Value (FAV) at the end of the 10-year battery lifespan compared to an investment at a 2% interest rate for the same period.

The most efficient model to calculate the investment income and expenses is a Total Cash Flow Model (TCM) which provides not only FAV but as well IRR, payback period (P), and Levelized Costs of Energy (LCOE).

2.1 Data requirements

The optimization of a PV-storage system relies heavily on measuring the energy flux that cannot be consumed instantaneously. This requires analyzing the correlation between generation potential and load demand. Therefore, the proposed strategy utilizes two primary input datasets with a minimum temporal resolution of one hour: site-specific meteorological data and load consumption profiles.

2.1.1 Weather Data of a Typical Meteorological Year (TMY)

The approach presented in this work uses hourly meteorological data from a Typical Meteorological Year (TMY) to estimate PV generation. A TMY is a synthesized annual weather data set composed of representative months selected from long-term historical records, typically covering 10–30 years. The TMY does not represent any single real year; instead, it is constructed by choosing, for each month, the historical month whose statistical characteristics most closely match long-term climate averages. Selection criteria generally include mean bias error, root-mean-square deviation, and other indicators of representativeness. The resulting data set captures the typical climate behavior of a location while excluding extreme or unusual events.

2.1.2 Hourly Load Consumption Data

The second required dataset is the hourly load profile. Similar to the creation of a TMY, it is possible to construct a representative annual load profile that reflects typical consumption patterns at a site. Alternatively, in contexts where consumption is highly deterministic, e.g., such as industrial facilities with programmed processes, measured load data can be used directly as a typical and representative workload. This profile is necessary for estimating IESC and for determining the amount of residual energy that must either be imported from or exported to the grid.

2.2 PV Plant Generation Capacity Simulation

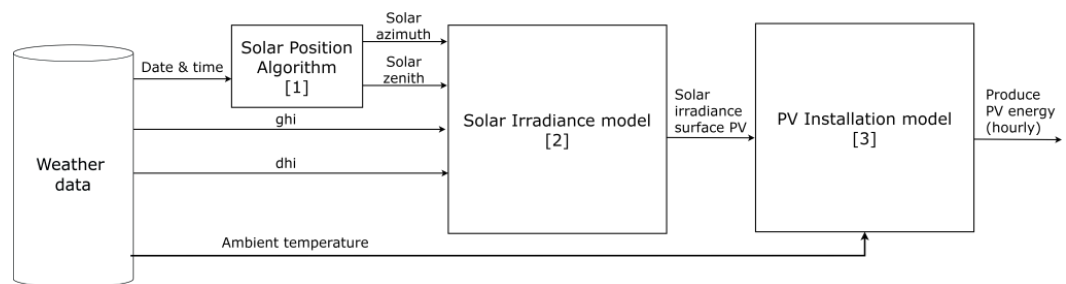
The proposed methodology separates the sizing of the PV generation capacity from the sizing of the battery storage capacity. The initial phase calculates the nominal PV capacity (P_{pv}) required to achieve a net-zero energy balance over a typical year, independent of

storage. The objective is to determine a P_{PV} value such that the net energy exchange with the grid (E_{grid}) approaches zero. Here, E_{grid} represents the cumulative sum of imported (positive) and exported (negative) energy over one year (8,760 hours).

Hourly PV production is estimated using a series of models (Figure 1). For each hour of the TMY, the position of the sun is computed following the algorithm in [1], providing the incidence angle of solar radiation on the module surface. Using this angle and the direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI), the effective plane-of-array irradiance is calculated using the transposition models described in [2]. The module temperature and the corresponding PV output power are modeled and estimated using the models indicated [3].

FIGURE 1:

Chain of models for estimating the PV power production



To generalize the results, the model utilizes the hourly specific energy yield, $Y(h)$, which represents the energy produced by a hypothetical 1 kWp PV system for each hour h . Therefore, the total energy produced by the plant at hour h is the product of the nominal capacity and the specific yield, i.e., $P_{PV} \cdot Y(h)$. Defining $E_L(h)$ as the load demand at hour h , the optimization problem seeks the P_{PV} that satisfies the following condition:

$$\sum_{h=1}^{8760} (E_L(h) - P_{PV} \cdot Y(h)) = 0 \quad (1)$$

Expression (1) can be solved analytically, i.e.,

$$P_{PV} = \frac{\sum_{h=1}^{8760} (E_L(h))}{\sum_{h=1}^{8760} (Y(h))} \quad (2)$$

2.3 PV Plant Battery Storage Simulation

Following the determination of the PV capacity, the methodology addresses the battery capacity (Q) and its relationship with grid interaction, a key determinant of economic profitability. The algorithm analyzes the energy balance for every hour of the year to quantify imported and exported energy. The fundamental energy balance equation (3) is given by:

$$E_L(h) = P_{PV} \cdot Y(h) + E_g(h) + E_s(h) \quad (3)$$

where $E_g(h)$ is the energy exchange with the grid at time h (positive for import, negative for export) and $E_s(h)$ is the energy exchange with the battery (positive for discharge, negative for charge). The proposed sizing strategy considers the hourly energy flow described in (3) to determine how much energy is imported to and exported from to the grid for a given battery capacity Q .

Note that the available energy in the battery is dynamic and depends on the system's state history. To minimize the degradation of the battery, the model incorporates a maximum Depth of Discharge (DoD) constraint of 80%, i.e., the effective usable capacity is limited to 80% of the nominal capacity (Q).

To determine the interaction with the grid, the sizing strategy consider two scenarios:

1. when the load demand exceeds PV generation (the deficit scenario) and
2. when the PV generation exceeds load demand (the surplus scenario).

The treatment of each scenario is described next.

2.3.1 Deficit scenarios

For each hourly interval, when the load demand exceeds the PV generation, the resulting deficit $E_{req}(h) = E_L(h) - P_{PV} \cdot Y(h)$ is first compared with the available battery energy $E_{avl}(h)$. The value of $E_{avl}(h)$ depends on the battery's state of charge (SOC). For instance, if the battery is fully charged (SOC = 1), it can supply energy up to its nominal usable capacity. As the SOC decreases, the amount of energy that can be delivered is reduced proportionally. This relationship is expressed as

$$E_{avl}(h) = SOC(h) \cdot Q \quad (4)$$

where Q is the nominal capacity of the battery. The SOC is updated at every time step to reflect the energy charged or discharged. Based on this formulation, the proposed sizing strategy applies equation (5) to determine the battery's energy contribution during deficit conditions.

$$E_s(h) = \begin{cases} E_{req}(h) & \text{if } E_{req}(h) < E_{avl}(h) \\ E_{avl}(h) & \text{if } E_{req}(h) > E_{avl}(h) \end{cases} \quad (5)$$

and any remaining deficit is imported from the grid:

$$E_g(h) = E_{req} - E_s(h) \quad (6)$$

2.3.2 Surplus scenarios

Conversely, when PV generation exceeds the load, the surplus energy E_{sup} is stored in the battery up to its remaining capacity $E_{cap}(h) = Q - E_{avl}(h)$. Similar to the deficit scenario, the energy that can be stored in the battery is determined according to equation (7).

$$E_s(h) = \begin{cases} E_{req}(h) & \text{if } E_{req}(h) < E_{avl}(h) \\ E_{avl}(h) & \text{if } E_{req}(h) > E_{avl}(h) \end{cases} \quad (7)$$

And any excess beyond the storage capacity is exported to the grid:

$$E_g(h) = E_{req} - E_s(h) \quad (8)$$

The algorithm accumulates the annual imported and exported energy, enabling the assessment of economic performance for different storage capacities. This procedure provides a systematic basis for determining the optimal battery size given the previously determined PV capacity and the site-specific meteorological and load conditions.

2.4 Profitability Concept and Profitability Assessment

Any investment, such as the investment in a PV system, involves sacrificing current money with the expectation of earning future money from the investment [4, p. 32]. An investment is financially profitable if the amount of returned future money is higher than the originally invested money. Therefore, investments are made based on expectations about the future.

Investment analysis uses cash flow models to analyze future income and expenses of an investment and to calculate the time-related value of money [5, p. 104]. Profitability is measured by the Net Present Value (NPV) or the Final Asset Value (FAV) of an investment alternative. The time value of money can be reflected in calculations either by discounting future cash flows to a NPV or by accruing compounded interest to a FAV at the end of the investment period.

Investing is the decision between at least 2 alternatives, i.e., to invest or not to invest. Financial analysis assesses the profitability of each option and selects the better option.

2.4.1 Discounted Cash Flows and Discount Rate

A cash amount held today, e.g. 100 EUR, and the same cash amount held in the future, e.g. 100 EUR in 10 years, do not have the same value. This concept of the time-related value of money is a fundamental part of investment theory [5, p. 104]. To compare the value of money at different points in time, future cash amounts are discounted to another point in time using an interest rate that reflects the time value of money given by equation (9). The interest rate is called the discount rate.

$$Value\ of\ money_{t+n} = Value\ of\ money_t * (1 + discount\ rate\ i)^n \quad (9)$$

The reason for the difference is that money held at time t can be invested, e.g. in a deposit account at an interest rate i and will have a higher value after n periods.

There is no general rule for determining the discount rate i, but it should reflect a realis-

tic increase/decrease in the value of money over time, taking into account [6, p. A3-11]

- the risk-free interest rate of the economy for the intended investment period
- plus a risk margin for the uncertainty of future cash flows.

The current risk-free interest rate for the Eurozone for different investment horizons is published by the European Central Bank on a daily basis (www.ecb.europa.eu/stats/financial_markets_and_interest_rates/euro_area_yield_curves/html/index.en.html).

The risk margin is specific to each investment project and varies depending on factors such as country risk, legal risk, technological risk, etc. which result in uncertainties about future cash flows. Each investor, as well as equity sponsor or debt lender, applies their own risk margin based on their individual assessment of the investment.

2.4.2 Net Present Value (NPV) and Final Asset Value (FAV)

If investing means sacrificing current money with the expectation of earning future money from the investment [4], then an investment is a financially profitable investment if the amount of future money returned is higher than the originally invested money. When evaluating different investment alternatives, the alternative with the highest positive NPV should be selected.

Based on this definition of profitability, the Net Present Value of the Free Cash Flow (FCF) of the investment measures the profitability. This leads in the definition of the Net Present Value (NPV) [5, p. 116] in equation (10):

$$NPV = \sum_{t=0}^N \frac{FCF_t}{(1+i)^t} \quad (10)$$

- If NPV is positive, then the investment returns more future money than invested, taking into account the time value of money at a specific discount rate i .
- If NPV is negative, then the investment returns less future money than invested, taking into account the time value of money at a specific discount rate i .

The Free Cash Flow (FCF) of an investment is the sum of equation (11)

- all cash invested until operational readiness of the investment (Investing Cash flow)
- all income and expenses generated from the operation of the investment (Cash flow from Operations)

$$Free\ Cash\ Flow_t = Cash\ Flow\ from\ Operations_t + Investing\ Cash\ Flow_t \quad (11)$$

Not only NPV but as well the Final Asset Value (FAV) represents the value of the investment since NPV and FAV

according to equation (9) are the same value but at a different points n in time leading to equation (12):

$$FAV_n = NPV * (1 + i)^n \quad \text{or} \quad NPV = FAV_0 \quad (12)$$

Accordingly, FAV_n follows the same rules as NPV:

- If FAV_n is positive, the investment returns more future money than invested money.

- If FAV_n is negative, the investment returns less future money than invested money.

In spreadsheets, FAV_n is easier to calculate than NPV. FAV_n equals the cumulative liquidity balance from investing cash flows and cash flows from operations at the end of each period, resulting in equation (13):

$$FAV_n = \sum_{t=0}^n (Investing\ Cash\ Flow_t + Cash\ Flow\ from\ Operations_t = FCF_t) * (1 + i)^{n-t} \quad (13)$$

2.4.3 Discounting Interest vs Accruing Compounded Interest

The time value of money can be calculated by either discounting future cash flows to a present value or by accruing compounded interest to a final value at the end of the investment period [5, p. 112].

Accruing compounded interest is easier to calculate in spreadsheet applications since the total cash balance at the end of each period is accrued with compounded interest into the next period:

$$Cash\ balance_t * (1 + discount\ rate\ i) = Cash\ balance_{t+1} \quad (14)$$

Grob [7, 8] uses this equation (14) to calculate FAV_N instead of NPV to assess the profitability of an investment. In Grob's cash flow models, any cash balance at the end of a period is virtually reinvested to show the effect of compounded interest. Additionally, the interpretation of FAV_n is straightforward since it represents the total liquidity balance held in bank account or cash at the end of the period n.

2.4.4 Investment Decision: Maximizing the Final Asset Value (FAV)

An investor decides between at least 2 alternatives, i.e. to invest or not to invest. Financial analysis assesses the profitability of each option and selects the better option. The better option provides the higher FAV_N . This statement is not trivial, since the FAV_N of the investment, e.g. in a battery storage of a PV, needs to be compared with the FAV_N value of the money after N periods if not invested. Without an alternative option, investment valuation is not possible.

2.5 Other KPIs to Compare Investment Alternatives

While FAV is the decisive criterion to select the best alternative, other Key Performance Indicators (KPIs) are used to describe the performance of an investment and help explain the difference between the optimal solution and less profitable solutions.

2.5.1 Internal Rate of Return (IRR)

Internal Rate of Return (IRR) is also used to assess investments. Investments should be accepted if IRR is greater than the discount rate i [5, p. 200]. IRR is defined in equation (15) as the discount rate which results in NPV of zero (0) for the FCF of an investment.

$$0 = NPV = \sum_{t=0}^N \frac{FCF_t}{(1+IRR)^t} \quad (15)$$

Thus, IRR equals the effective interest rate of a cash flow. Investment analysis criticizes

IRR for assessing investments because it can lead to misunderstandings [5, pp. 201-205]:

- Investment A with higher IRR_A than IRR_B for investment B does not necessarily result in a higher NPV_A than NPV_B or higher FAV_A than FAV_B , respectively.
- Due to the mathematical form of the equation for IRR, more than one IRR can solve the equation. But the economical interpretation of multiple IRRs for a single investment remains unclear. With a spreadsheet calculator like Excel, IRR is calculated with the Excel-function IRR. But excel finds only one IRR even if more than one IRR solves the equation.
- Furthermore, IRR does not reflect different investment volumes, or different investment periods or different discount rates of investments.

2.5.2 Payback Period (P)

The payback period (P) complements the measures to assess the profitability of an investment. The earlier the cumulative returns of an investment recover the investment volume, the lower the considered investment risk. When comparing two different investments with the same FAV_N and NPV respectively, the investment alternative with the earlier payback is considered to be less risky.

The payback period P is defined by expression (16) by accumulating the free cash flows (FCF) of the investment over time and indicating the first year with positive cumulative free cash flow

$$\sum_{t=0}^P (\text{Investing Cash Flow}_t + \text{Cash Flow from Operations}_t = FCF_t) * (1 + i)^n > 0 \quad (16)$$

Some authors criticize that investments can have negative free cash flows after reaching P. But this is only another reason why the payback period should not be relevant to select the best investment alternative.

2.5.3 Levelized Costs of Energy (LCOE)

Levelized Costs of Energy (LCOE) represent the discounted costs of an energy for an energy producing investment over its lifetime [9, p. 157f]. LCOE is defined by equation (17) and (18) respectively as

$$LCOE = \frac{\text{Present Value of costs of energy production}}{\text{Present Value of volume of produced ener}} \quad (17)$$

$$\text{or } LCOE = \frac{\sum_{t=0}^N \frac{\text{costs}_t}{(1+i)^t}}{\sum_{t=0}^N \frac{\text{energy production}_t}{(1+i)^t}} \quad (18)$$

LCOE represents the present value of discounted costs of energy production in relation to the present value of produced energy. LCOE is compared to the current price of consumed energy from the grid. If the price of energy is higher than LCOE, then investing in energy production could be reasonable. The discount rate i for calculation of LCOE should be the same discount rate used in the investment analysis.

2.6 Financial Investment Analysis Methodology

2.6.1 Total Cash Flow Model (TCM)

Total Cash Flow Models (TCM) analyze the cash flows of an investment and their development over the total investment period (N). TCM are spreadsheets containing rows of different cash flow items (income and expense) and columns of single periods (years, quarters, months) of the total investment period. The total investment period starts with the initial investment payment and ends with the useful lifetime of the investment ($t=N$).

Grob [7, 8] developed this modeling technique to enhance the understanding of investment analysis in university classroom discussions. Schulte et al. [10] have further developed this concept to analyze real estate investments, which typically have more complex cash flow models and more intricate financing and lending structures. In the meantime, TCM have become widespread in evaluating structured financing of complex investment projects [11].

By definition, the total sum of cash flows in a TCM in each period is the positive or negative change of liquidity held in bank account or in cash by the investment leading to equation (19)

$$\text{Liquidity change in period}_t = \text{Cash Flow from operations}_t + \text{Investing Cash Flow}_t + \text{Financing Cash Flow}_t \quad (19)$$

At the end of each period, the total liquidity balance is carried over to the next period, and interest is accrued on either cash deposits or cash debts to reflect the time value of money. (For further details refer to section 2.4.1).

If a PV investment is analyzed, then the total investment period is the useful lifetime of a PV system, e.g. 20 years, or of a battery storage, i.e. 10 years.

The line items in the rows of the TCM are all incoming and outgoing cash flows within a single period, such as money spent for investment (Capital Expenditures or CAPEX) or money spent for operation (Operational Expenditures or OPEX), as well as money received from different income sources. For financial analysis, cash flow items are grouped into three different categories of incoming and outgoing cash:

- Investing cash flows include all expenses until the investment is ready for operation, such as acquisition and preparation of the installation site, CAPEX for PV modules, inverters, batteries, charge controllers, monitoring equipment, tracking systems, wiring, mounting, grid connection, etc.
- Cash flows from operations include all income and expenses such as sales revenues from energy to the grid, savings from reduced grid consumption, interest income, yearly repair and maintenance expenses, tax payments, etc.
- Financing cash flows from investment sponsors (equity injections, equity withdrawals, and dividends) and from lenders (debt injections, debt repayments, and interest payments on debt).

If the TCM is used for discussion with international sponsors or lenders, it is recommended to use the definitions of the International Financial Reporting Standard IAS 7 for Cash Flow Statements (www.iasplus.com/en/standards/ias/ias7) as a guideline to group the cash items into cash flows from operations, investing cash flows, and financing cash flows.

The financial profitability of an investment is driven only by FCF of the investment, not by the financing cash flows (cf. section 2.4.2). Financing cash flows merely distribute earned future investment returns between sponsors and lenders of an investment. Different financing and capital structures only influence the distribution of future returns to equity sponsors and debt lenders but do not affect the value of an investment (Modigliani and Miller proposition, [5, pp. 469]).

For the financial analysis of a PV System, the methodology consists of four conceptual steps:

1. Preparation of incremental energy production datasets,
2. Financial valuation of energy flows (revenues from exported energy and costs of imported energy),
3. Analysis of investment-related annual incremental cash flows (cf. next paragraph), and
4. Calculation of investment key performance indicators such as Final Asset Value (FAV), Internal Rate of Return (IRR), Payback Period, or Levelized Costs of Energy (LCOE).

The first step processes the data produced by the technical simulation. Three quantities are essential: total PV generation, imported electricity, and grid feed-in electricity. These values are required for the already existing PV system without any expansion (base case) and for each expansion alternative. By comparing each expansion alternative with the base case, the model calculates the incremental energy generated, self-consumed, or exported as a result of investment.

In the second step, the incremental energy flows are converted into monetary values. Additional self-consumption reduces electricity procurement from the grid, and its economic value is determined by the electricity cost component derived from the consumer's power procurement contract. Incremental feed-in electricity in Germany is remunerated under Germany's market premium model, which consists of a monthly market value paid by the direct marketer and a premium paid by the grid operator. Operating expenses of the expansion such as maintenance, insurance, and metering are included as incremental annual costs.

In the third step, the incremental annual cash flows from incremental energy flows are calculated. These include lower costs from higher self-consumption, revenues from incremental grid feed-in, and all incremental operating expenses and income.

In the fourth step, the incremental TCM derives a complete set of profitability KPIs.

2.6.2 Incremental Analysis of PV Design Alternatives

Many investments do not start from scratch but are developed over stages or phases of an investment. Accordingly, an investment analysis should only focus on every cash not yet spent and analyze only the future cash flows related to the additional cash spent [5, pp. 206-208]. This type of incremental analysis measures only the profitability of additional cash investments, while investments of the past are considered sunk costs.

2.6.3 Pre-tax Comparison of PV Design Alternatives

Investment evaluation can be done using a cash flow from operations either before or after tax. Income tax is an expense item for the equity sponsors but not for the debt len-

ders, i.e. only the investment returns of equity sponsors are reduced by income tax payments. Since the financial profitability of an investment is only driven by the investing and the operating cash flows, and not by the financing cash flows, a pre-tax assessment already leads to optimal results. If required, the TCM can be extended by financing and tax-related cash flows but this only affects the different investment return distribution to sponsors and lenders.

2.7 Optimization Approach: Maximization of Final Asset Value of PV System

The FAV of a PV System represents the cash available either in cash or in a bank account at the end of the investment period. Choosing between different design alternatives of the PV System aims to maximize the FAV at the end of the useful lifetime of a battery storage, which is typically 10 years.

3. Results for an Agricultural Enterprise in Saxony-Anhalt, Germany

The proposed methodology is evaluated using a real agro-industrial enterprise located in Saxony-Anhalt, Germany. The company's core activities include precision farming services as well as seed cleaning and processing, all of which depend on electrically intensive machinery. As a result, the facility exhibits a high electricity demand profile, making on-site photovoltaic (PV) generation economically attractive. To further increase instantaneous energy self-consumption (IESC), the company is considering the integration of a battery energy storage system.

For the application of the methodology, the most recent complete year of electricity consumption data was selected. The company records its power demand at a 15-minute resolution; these data were aggregated to obtain an hourly load profile. The resulting dataset was examined for anomalies such as outliers or missing production data. No abnormalities were detected during the analyzed period.

The facility operates an existing PV installation that is currently in its third year of operation, with a total installed capacity of 433 kWp. The annual energy production of the system amounts to 485,498 kWh. Despite this generation, the facility still imports 366,245 kWh of electricity from the grid due to load patterns and periods of low solar availability, while 281,169 kWh of surplus PV energy were exported to the grid. The electricity purchase price is 19 ct/kWh, and the annual maintenance costs of the PV system are 3,184 EUR, representing the recurring operational expenditures associated with system upkeep.

To support the analysis, the existing PV system was simulated to estimate its hourly energy production over a typical meteorological year (TMY). The TMY data were obtained from the PVGIS database and synthesized using the solar radiation data set from Heliosat version 3 (SARAH3) for the period 2001–2025, following the methodology described in [12]. The PV module temperature was estimated based on the ambient temperature values provided in the same TMY dataset. The parameters used in the PV system simulation are summarized in Table 1.

Figure 2 presents the results of the hourly simulation for a representative day, highlighting four distinct operating conditions:

- In situation 1, the PV system does not generate electricity, the battery is discharged, and the entire load is supplied by the grid.
- In situation 2, PV generation exceeds the load demand, and the surplus energy is used to charge the battery, with no electricity imported from the grid.
- In situation 3, PV generation again exceeds the load, but the battery is fully charged; consequently, the excess energy is exported to the grid.
- In situation 4, PV generation is absent, and the energy demand is fully met by the battery.

FIGURE 2:

Simulation of the PV system with battery for a 21st of December.

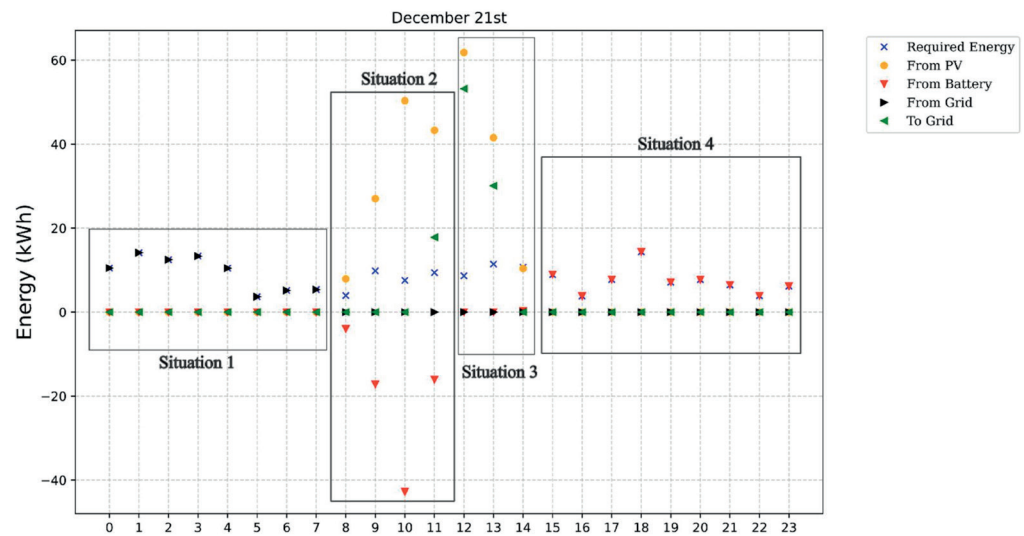


TABLE 1:

Parameters for the simulation of the PV system for the case study

Longitude	52
Latitude	11
Azimuth	South
Tilt angle of the PV installations	30°
PV Module technology	Monocrystalline Silicon, Monofacial
PV Module efficiency	22.2 %
PV Module power temperature coefficient	-0.29 % / °C
DC/AC efficiency	95.5 %

3.1 Existing PV system

The existing PV installation serves as the base case used to calculate the incremental cash flows of any further extension alternatives (Table 2). The economic analysis of the

existing PV system without a battery provides a FAV of 1.3 million EUR. This means that the existing installation, with an investment volume of 431,520 EUR, yields a FAV of 1.3 million EUR after 20 years. Using equation (12), a similar cash investment at an assumed discount rate i of 2% would yield a FAV_{20} of

$$FAV_{20} = 431,520 * (1 + 2\%)^{20} = 641,216 \quad (20)$$

The existing PV installation is by 633,083 EUR (=1,274,299–641,216) more profitable after 20 years than a capital market investment of 431,520 EUR at a 2% discount rate.

TABLE 2:

Total Cash Flow Model (TCM) of the existing PV installation (base case)

Period (t =)	0	1	2	3	4	5 ...	20
Cash Investment	431,520						
Investing Cashflow	-431,520						
Operational Cashflow							
+ yearly cost savings from on-site consumption	39,090	39,090	39,090	39,090	39,090	...	39,090
+ yearly income from surplus energy injection	16,540	16,540	16,540	16,540	16,540	...	16,540
OPEX							
-yearly maintenance costs	-3,184	-3,184	-3,184	-3,184	-3,184	...	-3,184
Free Cashflow	-431,520	52,446	52,446	52,446	52,446	52,446 ...	52,446
Investment of Cash Surplus @ discount rate 2%							
Cash disbursement	0	-52,446	-105,941	-160,506	-216,162	-272,931 ...	0
Cash repayment		0	52,446	105,941	160,506	216,162 ...	1,197,895
accrued interest on investment		0	1,049	2,119	3,210	4,323 ...	23,958
Total Cashflow Balance	0	0	0	0	0	0 ...	1,274,299

3.2 Potential Investment Alternatives: Energy Battery Storage with Capacity of 10 up to 19,995 kWh

It is considered whether an extension of the PV system with a battery storage improves the financial profitability, i.e. whether it increases the Final Asset Value after 10 years of the battery storage's useful lifetime. An incremental investment in a battery in period 3 of the PV system results in an improved Final Asset Value in year 13 (FAV_{13}) of the PV system.

Battery storage capacity between 10 and 19,995 kWh is technically feasible based on the hourly simulation model. The CAPEX is 250 EUR/kWh, with assumed operating expenses for yearly maintenance at 2% of the investment costs.

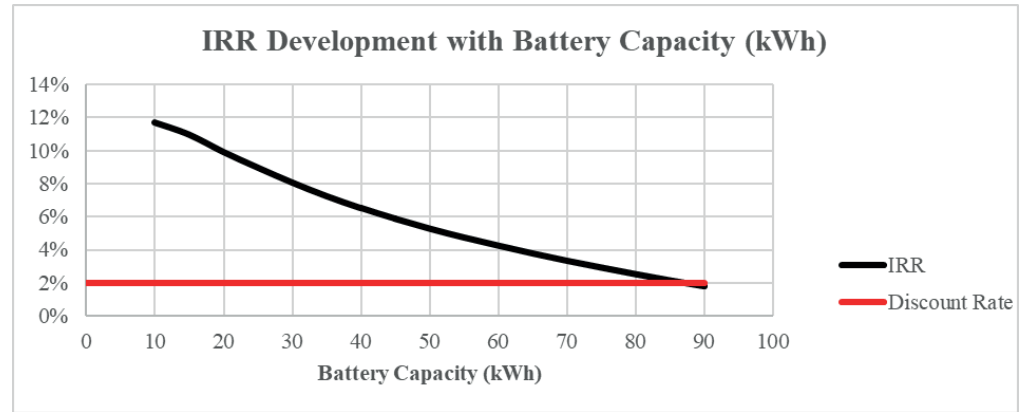
To narrow the variety of potential battery storage capacities, the IRR of investment in the different battery capacities is calculated. For each battery size, a TCM of the incremental cash flows for the periods 3 to 13 is evaluated, providing the IRR of the (incremental) FCF in figure 3.

Batteries with a capacity greater than 85 kWh provide an IRR of less than 2%, which is the discount rate in this case. Therefore, an investment in a battery greater than 85 kWh

will not increase the FAV. Accordingly, the further analysis will focus only on battery capacities smaller than 85 kWh.

FIGURE 3:

IRR development of different battery storage capacities (electricity import price 19 ct/kWh, electricity export income 6 ct/kWh, specific battery price 250 EUR/kWh)



3.3 Design of Total Cash Flow Model of the Battery Storage Extension

For a battery capacity of, e.g. 20 kWh, the Total Cash Flow model for 10 years from year 3 to year 13 is shown in table 3. The FAV_{13} of 2,776 EUR indicates that the investment in the battery storage yields 2,776 EUR more income than a cash investment of 5,000 EUR at a 2% interest rate over 10 years.

TABLE 3:

Total Cash Flow Model for Investment of 5,000 EUR in 20 kWh Battery Storage Capacity

Period (t =)	3	4	5	6	7	8	9	10	11	12	13
lower consumption from grid (kWh per year)	6,870	6,870	6,870	6,870	6,870	6,870	6,870	6,870	6,870	6,870	6,870
Energy to grid (kWh per year)	-6,870	-6,870	-6,870	-6,870	-6,870	-6,870	-6,870	-6,870	-6,870	-6,870	-6,870
Investing Cashflow	-5,000										
Operational Cashflow											
+ yearly cost savings from on-site consumption	1,314	1,314	1,314	1,314	1,314	1,314	1,314	1,314	1,314	1,314	1,314
+ yearly income from surplus energy injection	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404
OPEX											
-yearly maintenance costs	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Free Cashflow	-5,000	810	810	810	810	810	810	810	810	810	810
Financing of Cash Shortfall @ discount rate 2%											
Credit drawdown	5,000	4,290	3,565	2,827	2,073	1,304	520				
Credit repayment	-5,000	-4,290	-3,565	-2,827	-2,073	-1,304	-520	-520			
accrued interest on credit	-100	-86	-71	-57	-41	-26	-10				
Investment of Cash Surplus @ discount rate 2%											
Cash disbursement								-280	-1,096	-1,928	
Cash repayment									280	1,096	1,928
accrued interest on investment									6	22	39
Total Cashflow Balance	0	0	0	0	0	0	0	0	0	0	2,776
Final Asset Value (FAV ₁₃)	2,776										
Net Present Value (NPV)	2,278										
Internal Rate of Return (IRR)	9.9%										
LCOE [ct/kWh]	15.4										
Payback Period	10										

Payback Period

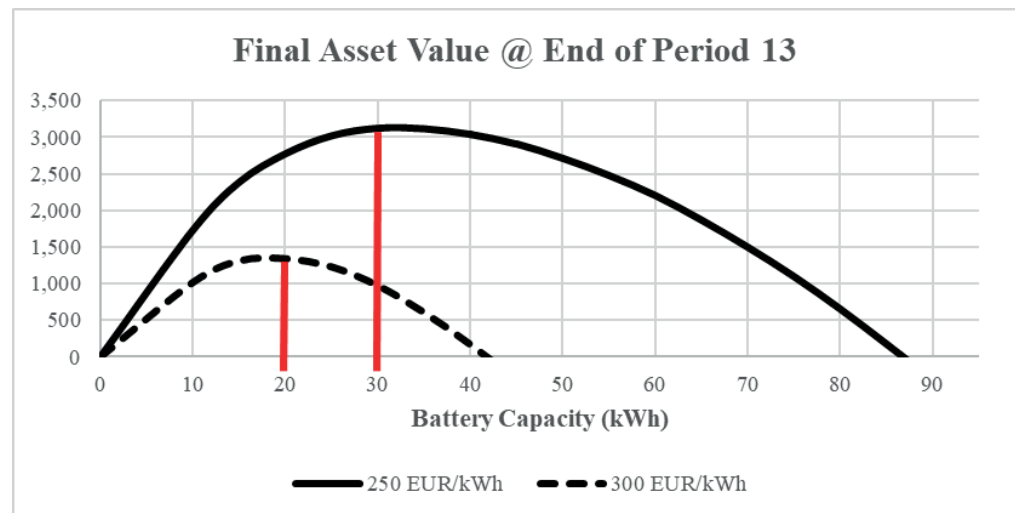
3.4 Comparison of Alternatives

For each investment alternative between 0 and 85 kWh battery storage capacity, the different KPIs are calculated based on the Total Cash Flow Model. The relevant KPI to select the optimal battery storage capacity is the FAV_{13} . Figure 4 shows the development of the FAV_{13} for the different battery storage options.

The option with the highest FAV_{13} is a battery capacity of 30 kWh. FAV_{13} is maximum at 3,125 EUR for an investment of 7,500 EUR at 250 EUR/kWh and a discount rate of 2%. The option with the highest FAV_{13} for a different pricing scenario is a battery capacity of 20 kWh. FAV_{13} reaches maximum at 1,338 EUR for an investment of 6,000 EUR at 300 EUR/kWh and a discount rate of 2%.

FIGURE 4:

Final Asset Value FAV_{13} of an investment in different battery storage capacities at specific battery costs of 250 EUR/kWh and 300 EUR/kWh.



3.5 Result: Optimal Battery Storage Size of 30 kWh at price of 250 EUR/kWh

For a battery capacity of 30 kWh, the Total Cash Flow model for 10 years from year 3 to year 13 is shown in table 4. The FAV_{13} of 3,125 EUR indicates that the investment in the battery storage yields a by 3,125 EUR higher income than a cash investment of 7,500 EUR at 2% interest rate over 10 years.

TABLE 4:

Total Cash Flow Model for Investment of 7,500 EUR in 30 kWh Battery Storage Capacity (Optimal Alternative)

Period (t =)	3	4	5	6	7	8	9	10	11	12	13
lower consumption from grid (kWh per year)	9,589	9,589	9,589	9,589	9,589	9,589	9,589	9,589	9,589	9,589	9,589
Energy to grid (kWh per year)	-9,589	-9,589	-9,589	-9,589	-9,589	-9,589	-9,589	-9,589	-9,589	-9,589	-9,589
Investing Cashflow	-7,500										
Operational Cashflow											
+ yearly cost savings from on-site consumption	1,834	1,834	1,834	1,834	1,834	1,834	1,834	1,834	1,834	1,834	1,834
+ yearly income from surplus energy injection	-564	-564	-564	-564	-564	-564	-564	-564	-564	-564	-564
OPEX											
-yearly maintenance costs	-150	-150	-150	-150	-150	-150	-150	-150	-150	-150	-150
Free Cashflow	-7,500	1,120	1,120	1,120	1,120	1,120	1,120	1,120	1,120	1,120	1,120
Financing of Cash Shortfall @ discount rate 2%											
Credit drawdown	7,500	6,530	5,540	4,530	3,501	2,450	1,379	286			
Credit repayment	-7,500	-6,530	-5,540	-4,530	-3,501	-2,450	-1,379	-286			
accrued interest on credit	-150	-131	-111	-91	-70	-49	-28	-6			
Investment of Cash Surplus @ discount rate 2%											
Cash disbursement									-829	-1,965	
Cash repayment										829	1,965
accrued interest on investment										17	39
Total Cashflow Balance	0	0	0	0	0	0	0	0	0	0	3,125
Final Asset Value (FAV ₁₃)	3,125										
Net Present Value (NPV)	2,564										
Internal Rate of Return (IRR)	8.1%										
LCOE [ct/kWh]	16.2										
Payback Period	11										

↑
Payback Period

3.6 KPI calculation of the Optimal Alternative

The NPV is calculated as follows:

$$NPV = \frac{FAV_{13}}{(1 + \text{discount rate } i)^{10}} = \frac{3,125}{(1 + 2\%)^{10}} = 2,564 \quad (21)$$

The IRR of 8.1% is calculated for the Free Cash Flow sequence of (-7,500; 1,120; 1,120; 1,120; 1,120; 1,120; 1,120; 1,120; 1,120; 1,120) by solving equation (15).

LCOE includes not only direct expenses but also indirect expenses representing the lower income from grid-feeding (opportunity costs) of -564 EUR per year. The present value of energy yield is 86,131 kWh, and the present value of energy costs is 13,914 EUR, resulting in LCOE of 16.2 ct/kWh for the recovered energy.

The payback period P is reached after 8 years in period 11, as soon as the cash surplus is greater than 0 and can be reinvested.

4. Discussion of Sensitivities of the Optimal Result

The optimal investment to extend the existing PV system is a battery storage with a capacity of 30 kWh for 7,500 EUR in year 3. The battery recovers 9,589 kWh of energy per year. This results in higher self-consumption of produced energy and reduces energy import from the grid at 19 ct/kWh. However, export to the grid at 5.9 ct/kWh is reduced accordingly. The additional yearly income of 1,834 EUR is offset by yearly maintenance expenses of 150 EUR, or 2% of the investment. Consequently, a yearly positive free cash flow of 1,120 EUR pays back the investment in year 11, i.e. after 8 years, and provides an additional final asset value including accrued interest at 2% (discount rate) of 3,125 EUR.

If key parameters of the solution vary, then the optimal result will change accordingly:

- The electricity price has the highest impact on the optimal battery size (figure 5). A lower electricity price than 19 ct/kWh would reduce the profitability and the optimal battery size would be smaller as well. A lower price than 16.2 ct/kWh (= LCOE) would almost eliminate all intended financial benefits of a battery storage.
- An increase in battery costs by 20% to 300 EUR/kWh would reduce the optimal battery capacity to 20 kWh (figure 4), lower battery costs would increase the optimal battery capacity. The investment would be less profitable but would pay back 1 year earlier.
- An increase in the discount rate would reduce the profitability of the optimal solution since the positive free cash flow would yield lower accrued interest compared to a capital market investment (figure 6).

FIGURE 5:

Final Asset Value FAV_{13} of an investment in different battery storage capacities at energy prices of 16 ct/kWh, 19 ct/kWh, and 21 ct/kWh.

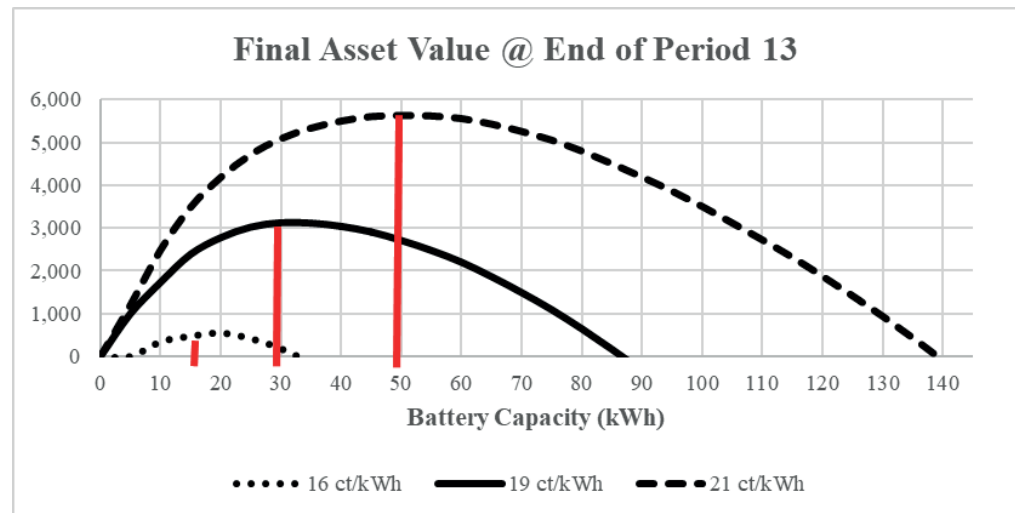
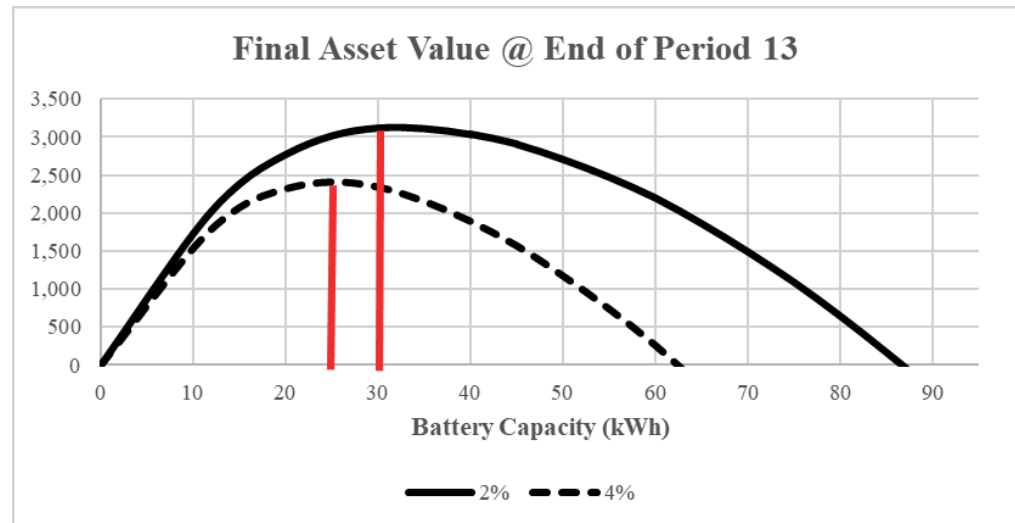


FIGURE 6:

Final Asset Value FAV_{13} of an investment in different battery storage capacities at discount rates of 2% and 4%.



5. Conclusions and Outlook

This article presents a transparent cash flow-based methodology that translates technical energy balances into financially relevant indicators for investment decision-making. The proposed framework is reproducible and applicable in practical contexts, even when only annual data are available. By employing an incremental analysis approach, the study illustrates how investment decisions for existing PV systems can be significantly improved. The methodology determines the optimal battery capacity by maximizing the final asset value, providing a clear and practitioner-oriented decision criterion. FAV can only be positive when the investment returns are higher than a cash investment at the capital market discount rate. Thus, increasing market interest rates make a battery investment less attractive. The results also demonstrate that increasing battery capacity generates economic value only when the incremental cost savings exceed both the additional investment costs and the loss of feed-in revenues. The key drivers for profitability improvement of batteries are the specific price in EUR/kWh for investment in a battery and the useful lifetime of a battery of only 10 years.

For the analyzed case, the integration of a battery system does not result in a significant improvement in the overall profitability of the combined PV and storage installation. Due to the specific energy load profile the incremental energy yield of a battery is low compared to the incremental costs, resulting in high LCOE of 16.2 ct/kWh even for the optimal battery size. Thus, the incremental margin of energy savings income at a price of 19 ct/kWh minus LCOE is rather small to recover the investment costs in a battery lifespan of only 10 years. Nevertheless, it is reasonable to assume that the implementation of a demand management system could increase instantaneous energy self-consumption, potentially enhancing the economic attractiveness of battery investments.

Additionally, this study does not account for the potential benefits associated with the reduction of power demand peaks, which constitute a relevant component of the company's electricity bill. In this context, battery storage systems can provide peak-shaving capabilities, leading to additional cost savings for industrial consumers. The systematic

evaluation of demand-side management strategies and peak-shaving effects therefore represents a natural next step in the analysis of the economic viability of PV and battery storage systems.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

While preparing this manuscript, the authors did NOT use AI-assisted technologies. The authors have thoroughly reviewed and revised the content of the article and accept full responsibility for the final version.

ABBREVIATIONS

CAPEX (Capital Expenditures), **CF** (Cash Flow), **ct** (Cents), **DCF** (Discounted Cash Flow), **DHI** (Diffuse Horizontal Irradiance), **DNI** (Direct Normal Irradiance), **DOD** (Depth of Discharge), **EUR** (Euro), **FAV** (Final Asset Value of the investment), **FCF** (Free Cash Flow), **GHI** (Global Horizontal Irradiance), **IESC** (Instantaneous Energy Self-Consumption), **IRR** (Internal Rate of Return), **KPI** (Key Performance Indicator), **kWh** (Kilowatt hours), **kWp** (Kilowatt peak), **LCOE** (Levelized Costs of Energy), **N** (Number of Investment Periods, lifespan of the investment), **NPV** (Net Present Value), **OPEX** (Operating Expenditures), **PV** (Photovoltaic), **ROI** (Return on Investment), **SARAH3** (Solar Radiation Data Set from Heliostat version 3), **SOC** (State of Charge), **TCM** (Total Cash Flow Model), **TMY** (Typical Meteorological Year)

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